University of Massachusetts UMASS Lowell

Master's Thesis Defense

Finite Element Analysis for the Damage Detection of Light Pole Structures

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Outline

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- Objective
- Literature Review
- Approach
- Finite Element Modeling
- Results and Discussion
- Proposed Damage Detection Methodology
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Introduction

In December 2009, a 200-pound corroded light pole fell across the southeast expressway in Massachusetts.[1]

(Source: [1] I-team: Aging light poles a safety concern on mass. roads)

Introduction

1. Failure of light poles are critical as they are typically located adjacent to roadways, highway and bridges.
2. Failures of aging light poles can jeopardize the safety of residents and damage adjacent structures. (e.g., residential houses, and electricity boxes.)

(Photo source: www.news-leader.com)

(Photo source: www.news-leader.com)

Therefore, aging light poles need to be repaired or removed before residents get hurt.

Objective

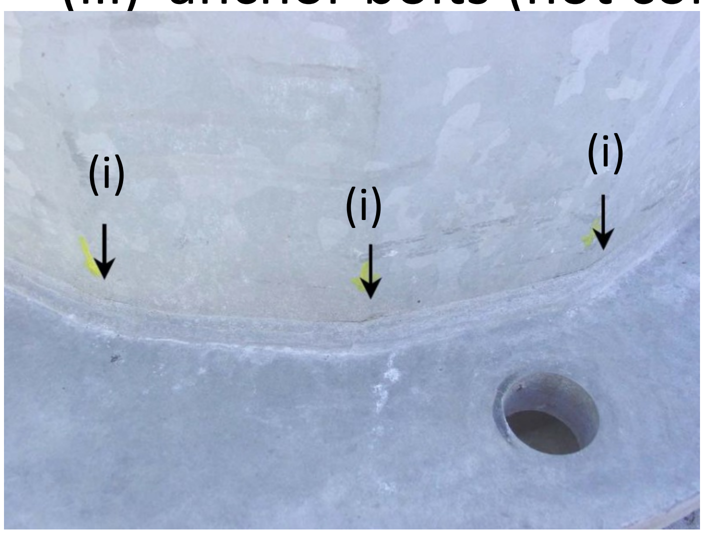
To develop a damage detection methodology for light pole structures using modal frequencies and mode shapes extracted from their free vibration responses

Literature Review

- How do damages affect light poles in terms of mechanical responses?
- Where do damages usually occur in a light pole?
- How can we locate and quantify damages using the mechanical responses of light pole?

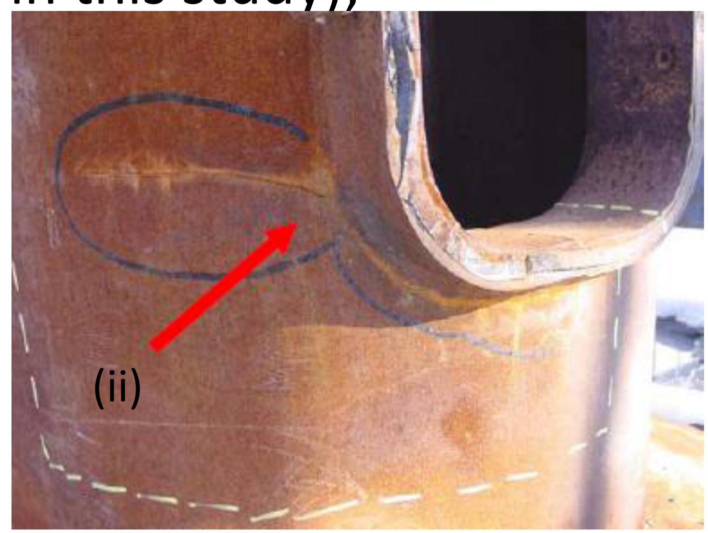
Literature Review

1. There are three most common/possible damage locations in light poles (Garlich and Thorkildsen (2005) [14] , Caracoglia and Jones (2004)[7]; Conner et. al. (2005)[6])
   (i) pole-to-baseplate connection,
   (ii) handhole detail, and
   (iii) anchor bolts (not considered in this study);



Cracks at bottom of the pole

(Photo source: http://polesafety.com)



Cracks at handhole detail

(Photo source: http://polesafety.com)

Literature Review

2. Changes in modal frequencies and mode shapes are expected while introducing damages into structures. (Lee and Chung (2000) [44]; Abdo and Hori (2002)[4])

For example, the modal frequency of an undamped single degree of freedom (SDoF) structure can be determined by following equation: $\omega=\sqrt{k/m}$

where ω is the modal frequency, k is stiffness of the structure, and m is mass of structure.

Since the presence of damages reduces k (stiffness) of the structure.

Consequently, $k\downarrow \Longrightarrow \omega\downarrow$

Literature Review

3. Structural damages in light poles can be simulated by reducing materials' properties (i.e. Young's modulus) in numerical simulation. (Yan *et. al*. (2006) [42])

For example, the stiffness of a cantilever beam (SDoF) can be written as:

$$k=3EI/h3$$

where E is Young's modulus of material, and I is the mass moment of inertia, and h is the height of this beam.

$$E\downarrow \Longrightarrow k\downarrow$$

Literature Review

4. Experimentally capturing dynamic characteristics (such as modal frequencies and mode shapes) of light poles is difficult and time consuming. (Yan *et. al.* (2007)[43])

Literature Review

- How do damages affect light poles in terms of mechanical responses?
  → There will be changes in modal frequencies and mode shapes.

- Where do damages usually appear in a light pole?
- → There are three common damage locations.

- How can we locate and quantify damages using the mechanical response of light poles?
  → Need a damage detection method.
  → Use numerical simulation to develop the method.

Approach

Proposed research approach is determined based on:

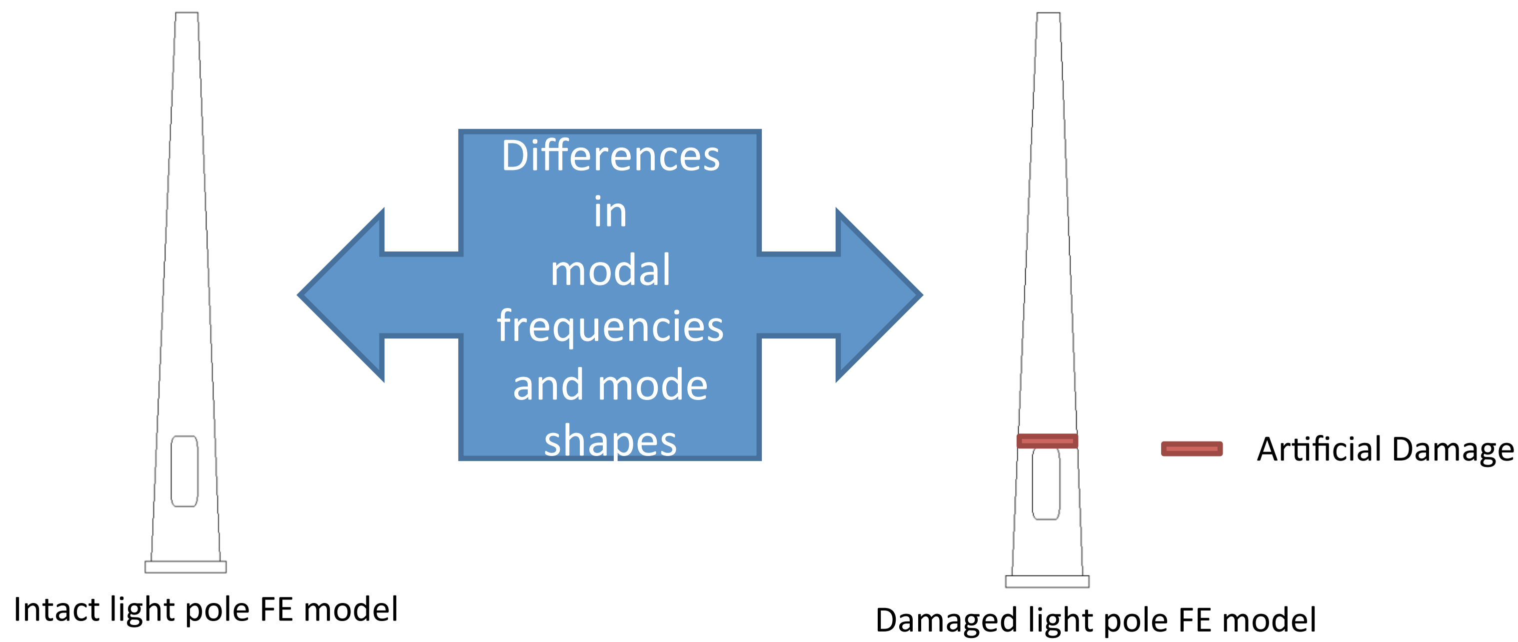
1. Assuming damages only occur at three most common damage locations.

2. Using dynamic responses (i.e., modal frequencies and mode shapes) as parameters for investigating differences between intact and damaged light poles.

3. Using numerical methods (i.e., finite element (FE) method).

Approach

Simulate intact and damaged light poles by the FE method, and study the differences in modal frequencies and mode shapes between intact and artificially damaged FE models.

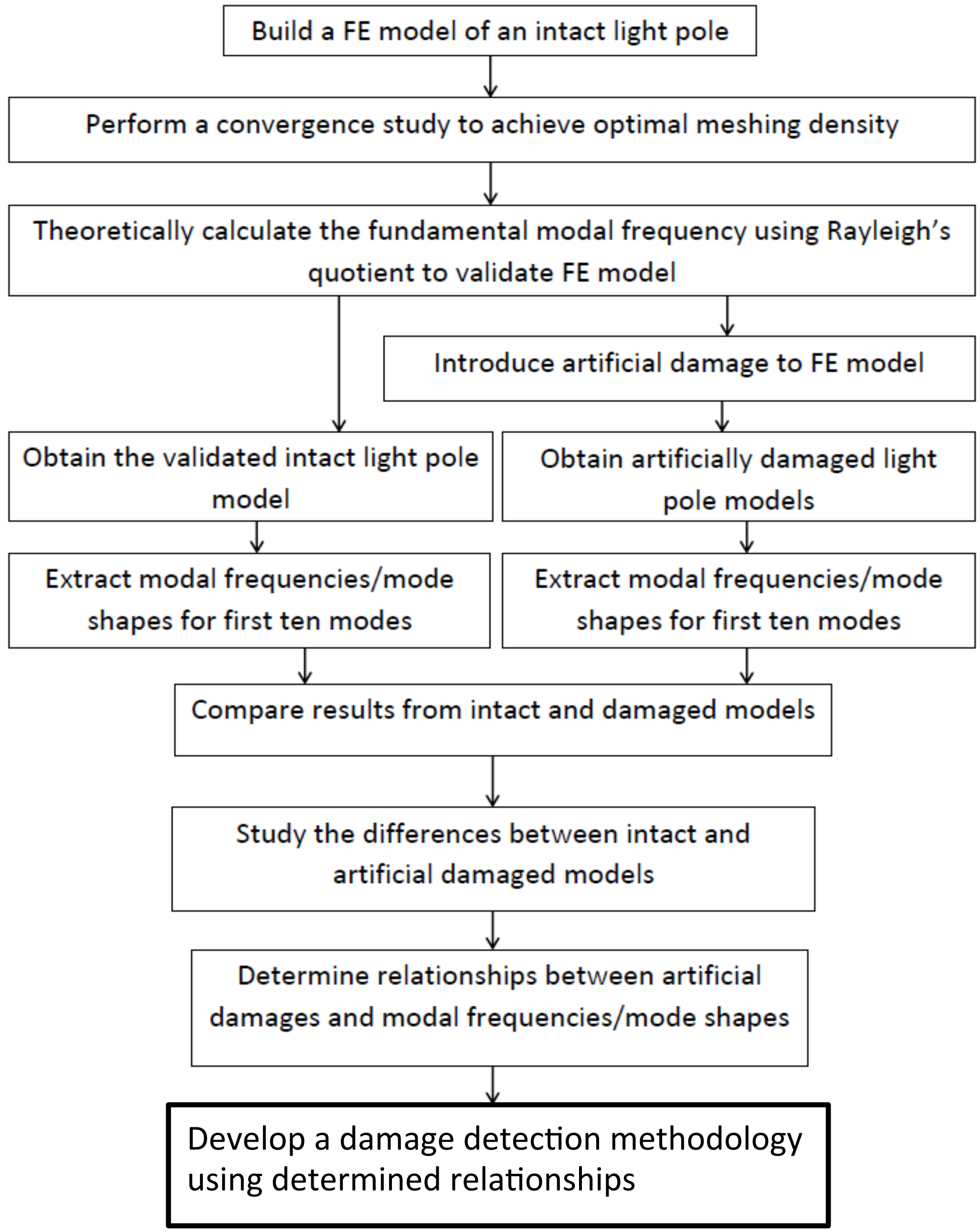


Approach

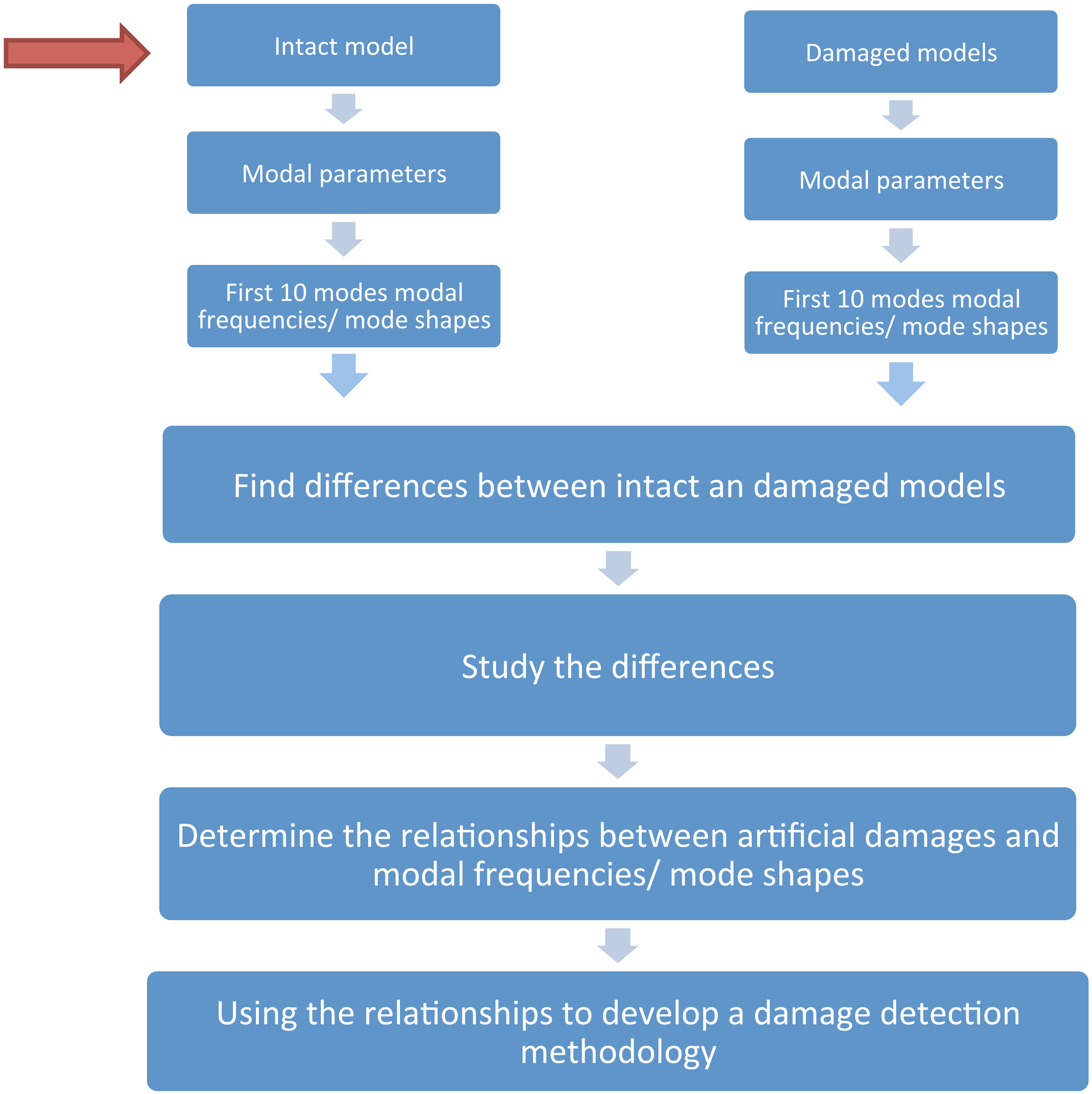
Assumptions :

- First ten modal frequencies are available.
- FE light poles are undamped.
- Damages only occur at pole-to-baseplate connection, and handhole detail.
- There is only one damage in each artificially damaged light pole model.
- A commercial FE package ABAQUS® (Dassault Systèmes) is used.

Research Methodology



Roadmap


Intact model
Damaged models
Modal parameters
Modal parameters
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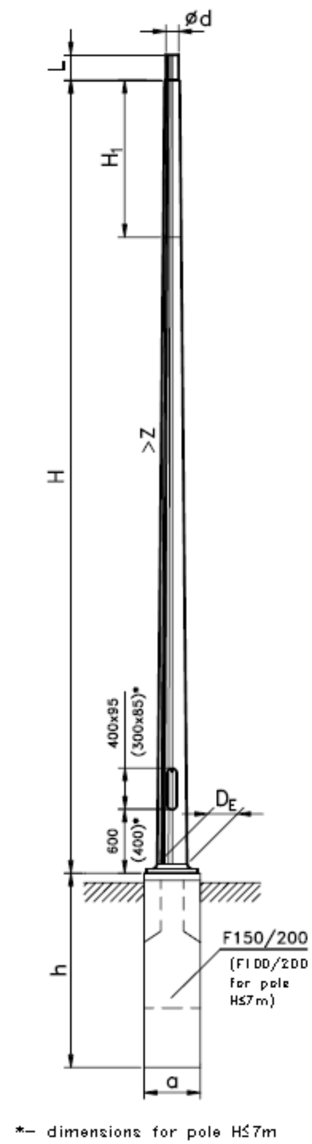
Finite Element Modeling
Configurations of an Example Light Pole

(source: ELEKTROMONTAŻ RZESZÓW SA*: Lighting poles and masts,*2009)



Finite Element Modeling

Technical data

TYPE	H	t_{bl}	H_1	⌀d/D_E	L	m	S	axaxh Type
	m	mm	m	mm	mm	kg	m^2	m
S-60SRwP/4	6		2,0	48; 60/140		68,0	1,47	0,3x0,3x1,0 F100/200
S-70SRwP/4	7		2,0			79,0	1,71	
S-80SRwP/4	8		2,2			96,0	2,76	
S-90SRwP/4	9	4	2,5		100	104,0	3,41	
S-100SRwP/4	10		3,5	48; 60/170		110,0	3,65	0,3x0,3x1,5 F150/200
S-110SRwP/4	11		2,2			128,0	3,89	
S-120SRwP/4	12		3,2			135,0	4,22	

Note: H_1 – reduction piece for straight pole is ordered as separate element.

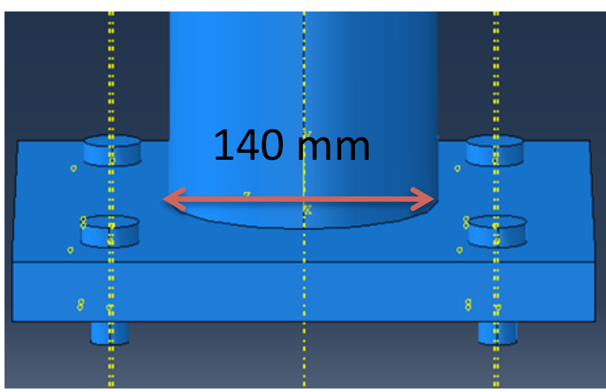
(source: ELEKTROMONTAŻ RZESZÓW SA*: Lighting poles and masts,*2009)

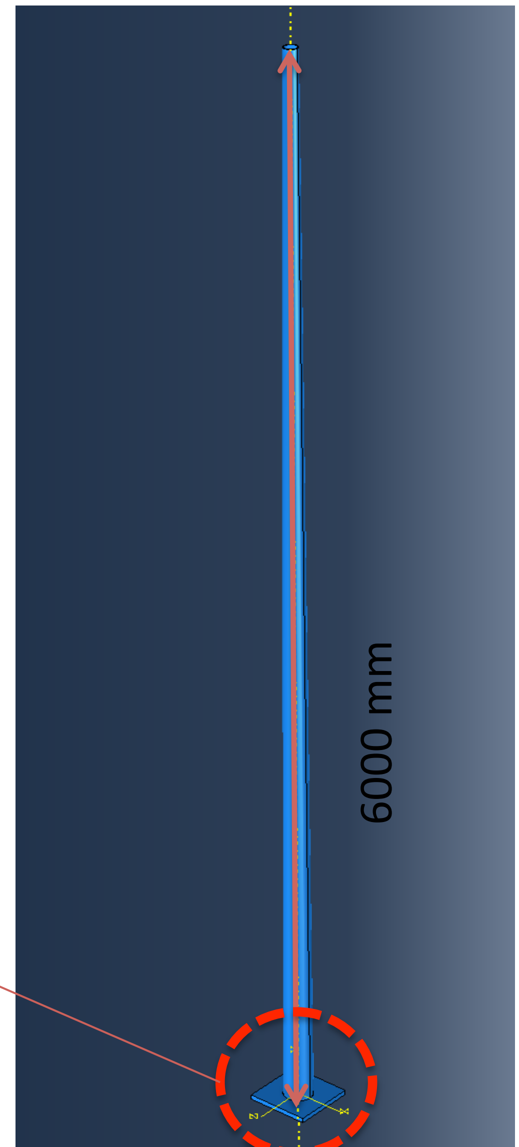
-- Chosen geometry

Finite Element Modeling

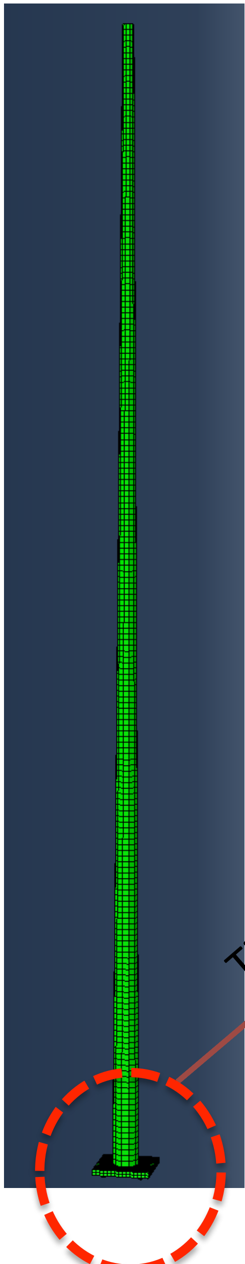
Materials (steel) & Geometries

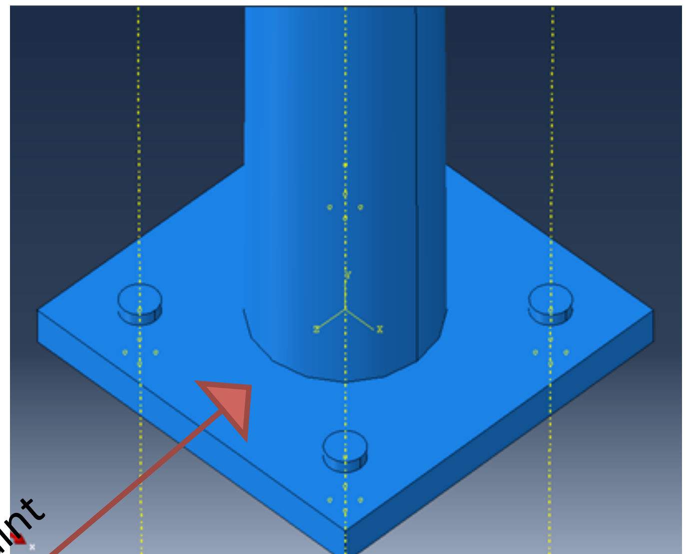
Density:	7.85E-09 ton/mm^3
Young's Modulus:	207,000 MPa
Poisson's ratio:	0.3
Yield stress:	450 MPa
Length of the pole:	6,000 mm
Diameter at top:	60 mm
Bottom:	140 mm

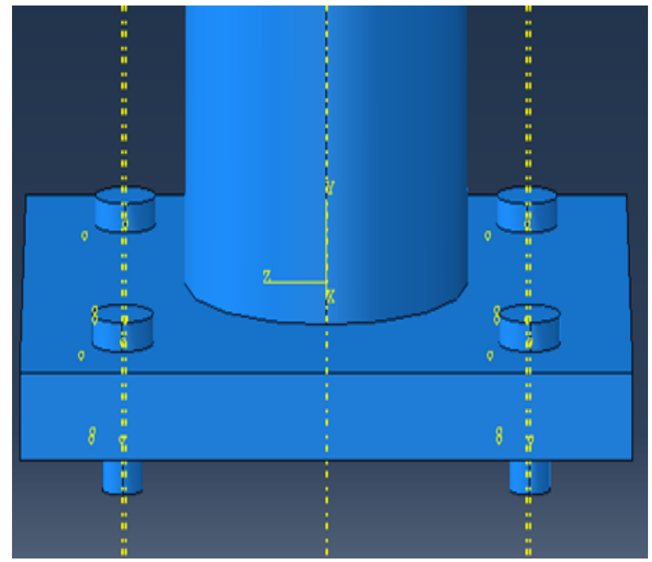




Baseplate Model

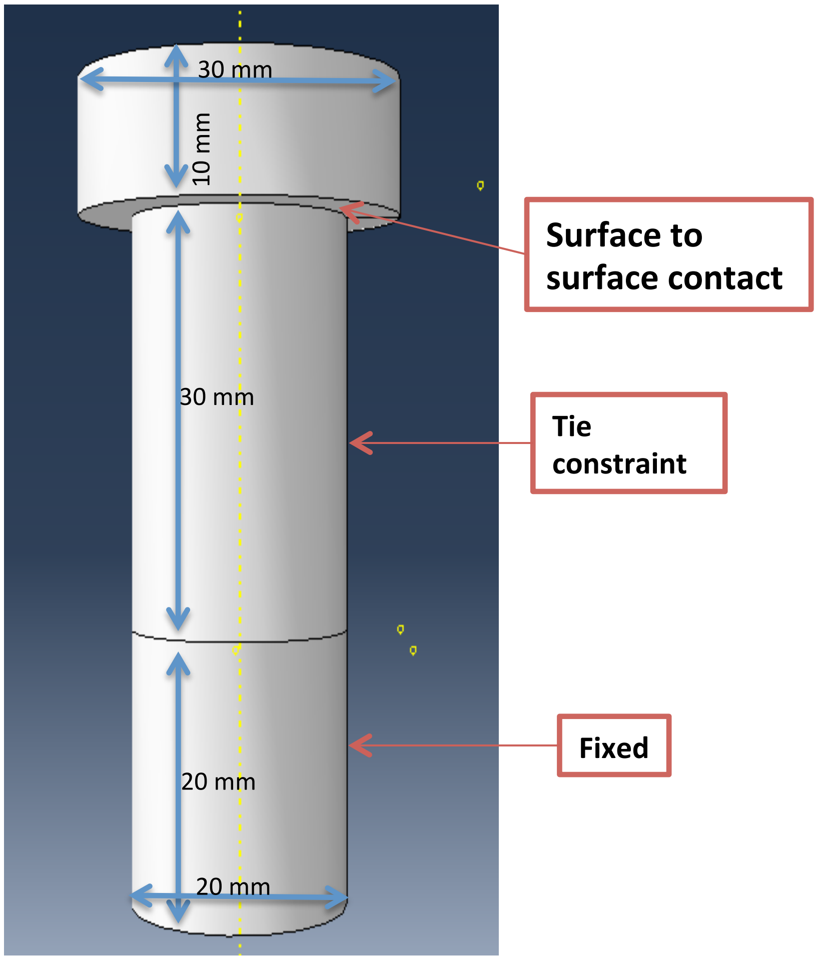


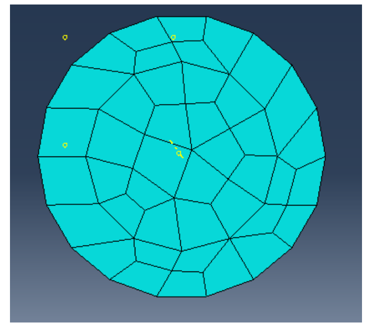


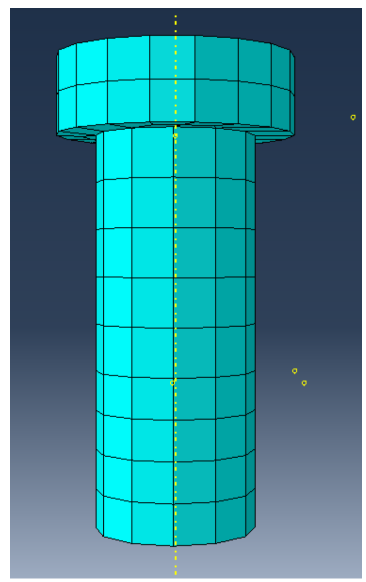


- Baseplate size: L x W x H: 300x300x30 (mm)
- Boundary condition: Tie constraint is used to assemble the pole and the baseplate.

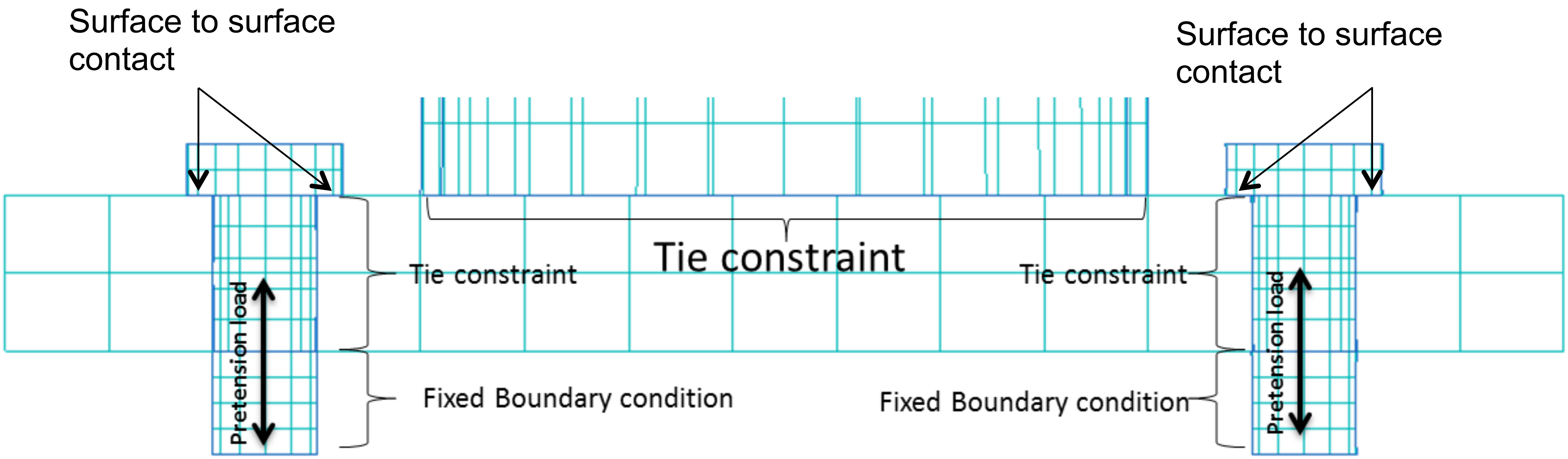
Bolt Models

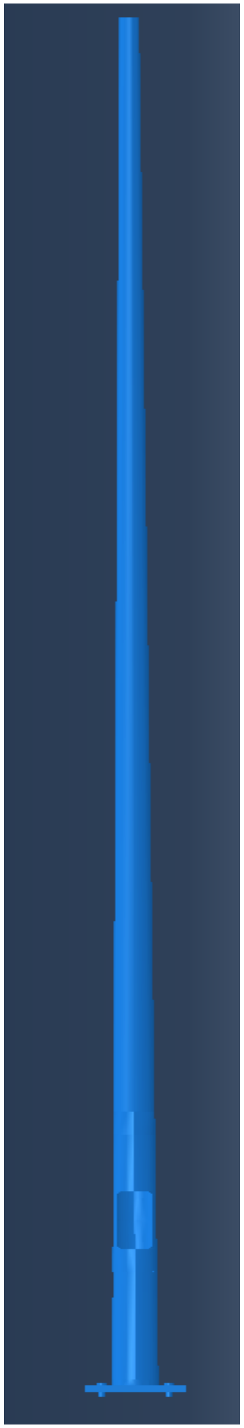

30 mm
10 mm
30 mm
20 mm
20 mm
Surface to surface contact
Tie constraint
Fixed



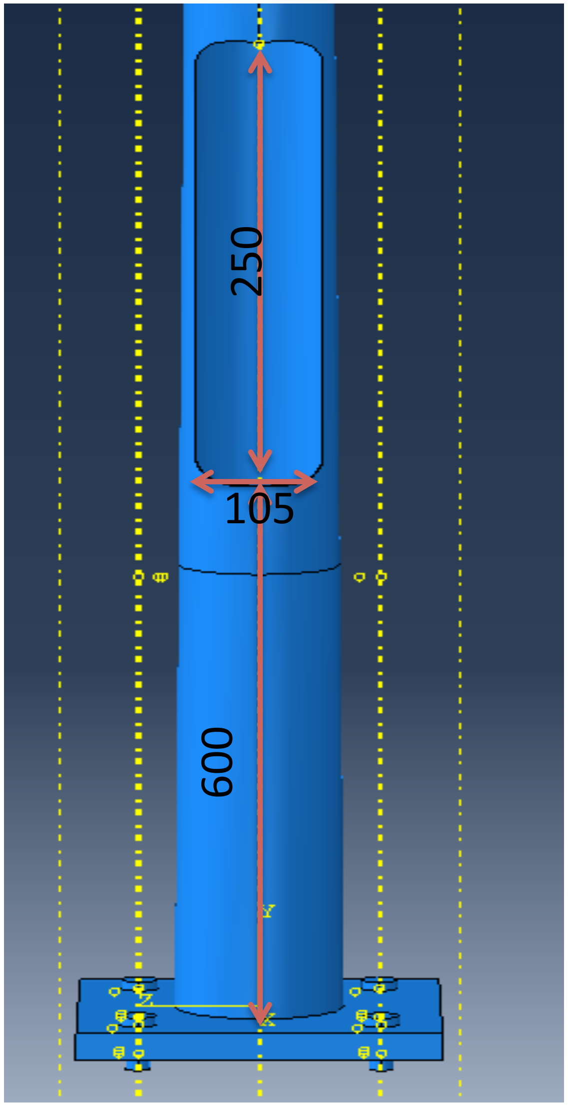


Baseplate Model





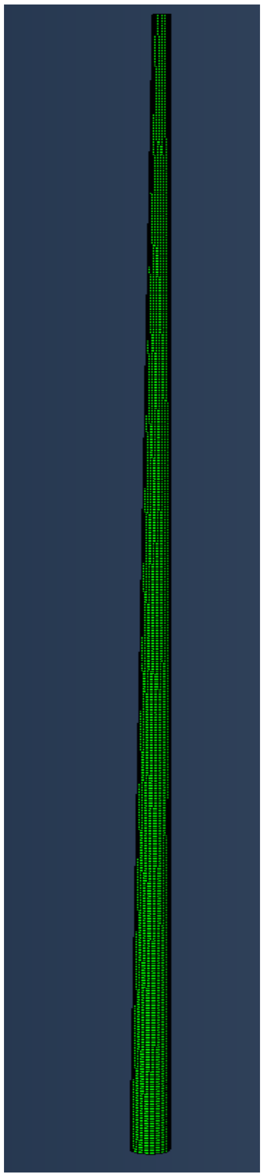
Handhole



Handhole size:
250x105

(Dimension: mm)

Verification of an Intact FE Pole Model



An intact FE pole model was verified by comparing the first modal frequency between the FE result and theoretical calculation.

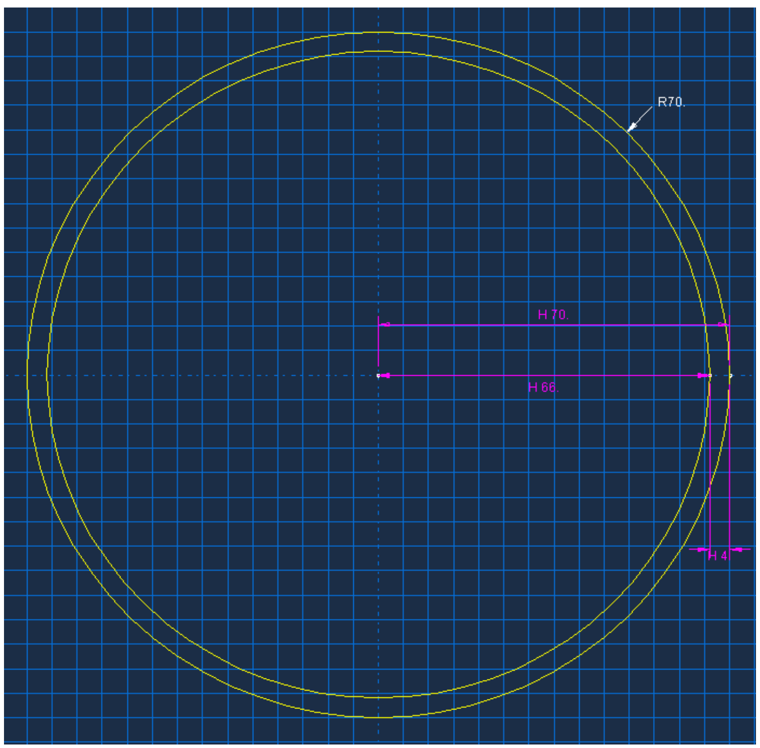
First modal frequency of the FE pole model created in ABAQUS®
is : **4.236 Hz (FE result).**

0	Increment	0: Base State				
1	Mode	1: Value =	708.22	Freq =	4.2355	(cycles/time)
2	Mode	2: Value =	708.22	Freq =	4.2355	(cycles/time)
3	Mode	3: Value =	14192.	Freq =	18.960	(cycles/time)
4	Mode	4: Value =	14192.	Freq =	18.960	(cycles/time)
5	Mode	5: Value =	89791.	Freq =	47.691	(cycles/time)
6	Mode	6: Value =	89791.	Freq =	47.691	(cycles/time)

Theoretical Calculation

Given:

Density:	7.85E-09 Ton/mm^2
Young's Modulus:	207000 MPa
Poisson's ratio:	0.3
Yield strength:	450 MPa
Length of the pole:	6000 mm

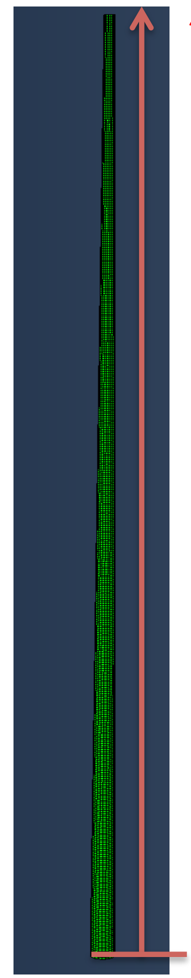


R=70mm;
r=66mm

Cross section at bottom of the pole(x=0)

X=6000

R=30mm;
r=26mm



X=0

R=70mm;
r=66mm

Theoretically Computed First Modal Frequency

1.Radius functions

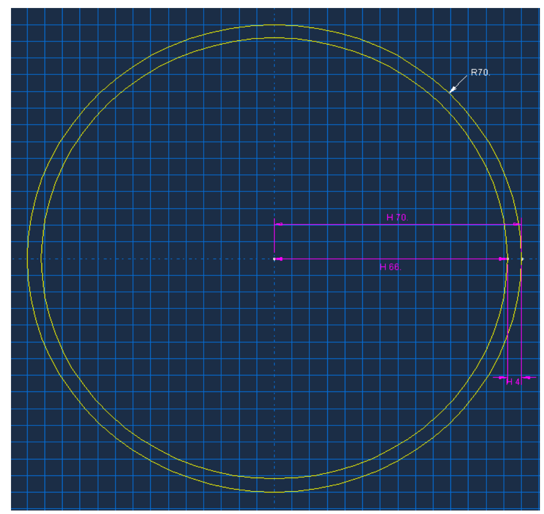
Radius of external edge: $$R(x) = \frac{1}{-150}\cdot x + 70$$

Radius of internal edge: $$r(x) = R(x) - 4$$

2.Distribution functions for mass and mass moment of inertia

$$m(x) = \pi\cdot\left(R(x)^2 - r(x)^2\right)\cdot 7.85\cdot 10^{-9}$$

$$I(x) = \left(R(x)^4 - r(x)^4\right)\cdot\frac{\pi}{4}$$



Theoretically Computed First Modal Frequency

3.Generalized mass, and generalized stiffness

$$m' = \int_0^L m(x)\,\psi(x)^2\,dx$$

$$k' = \int_0^L E\cdot I(x)\cdot\left(\frac{d^2}{dx^2}\psi(x)\right)^2 dx$$

Eq. 8.3.12

Anil K Chopra. *Dynamics of structures-Theory and applications to earthquake engineering.* Pg.312

where ψ(x) is shape function of cantilever beams. The best-fit shape function is the one which provides lowest value of first modal frequency among three given shape functions.

Theoretically Computed First Modal Frequency

First modal frequency: $$\omega := \left(\frac{k'}{m'}\right)^{0.5}$$

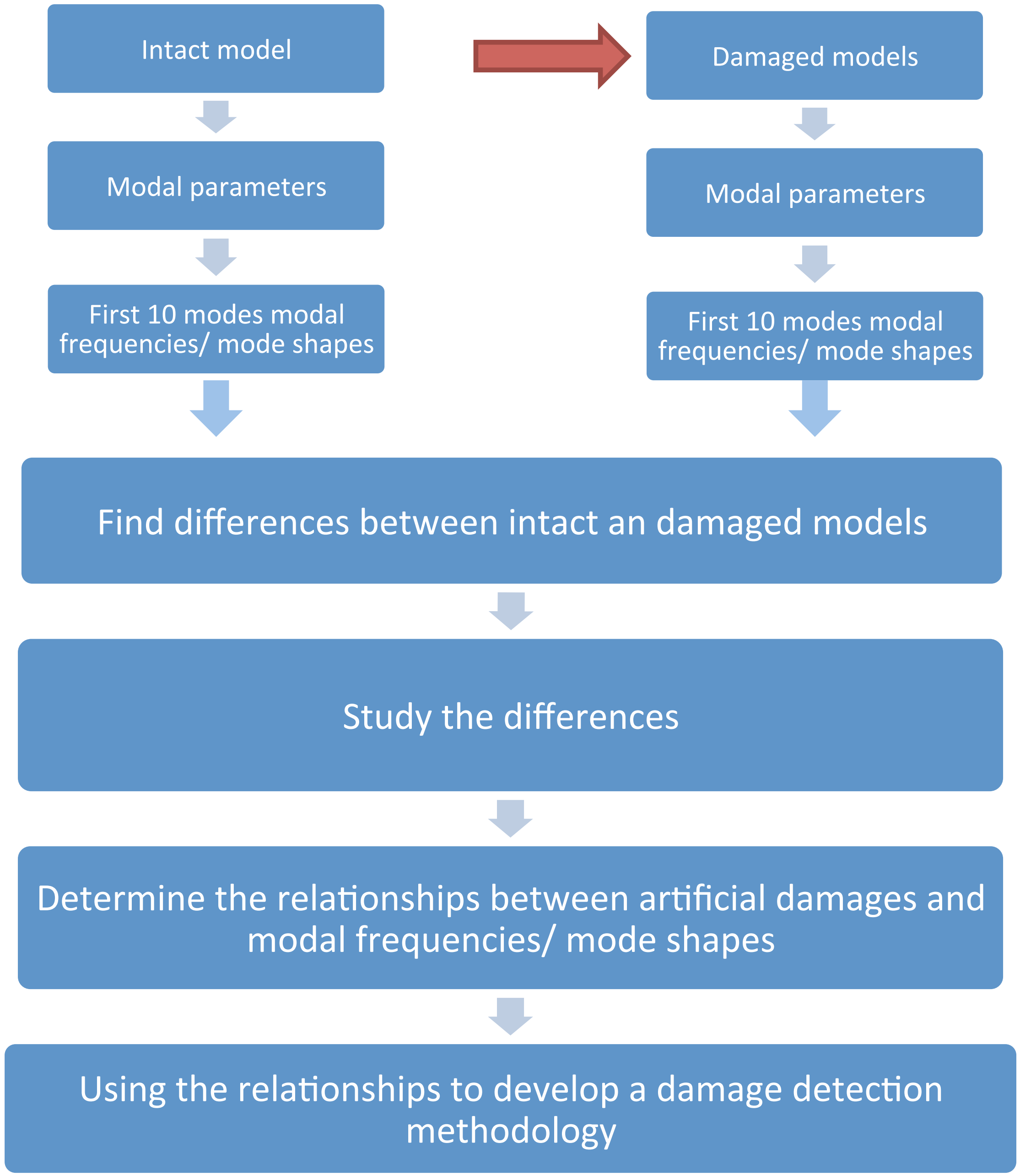
Shape function	$\psi(x) := \frac{3x^2}{2\cdot 6000^2} - \frac{x^3}{2\cdot 6000^3}$	$\psi(x) := 1 - \cos\left(\frac{\pi \cdot x}{2\cdot 6000}\right)$	$\psi(x) := \frac{x^2}{6000^2}$
f (Hz)	4.361	4.298	4.396

Theoretical result: The lowest value of first modal frequency is **4.298 Hz.**

FE result: **4.236 Hz**

→ Only 1.4% of difference. This means the FE result is correct and accurate.

Roadmap


Intact model
Damaged models
Modal parameters
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First 10 modes modal frequencies/ mode shapes
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Find differences between intact an damaged models
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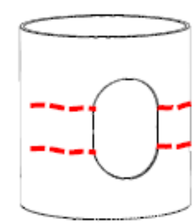
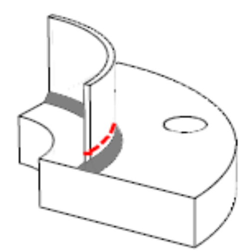
Finite Element Models

Damaged models

Damaged models were simulated by introducing artificial damages to intact light pole models.

Damage Simulations

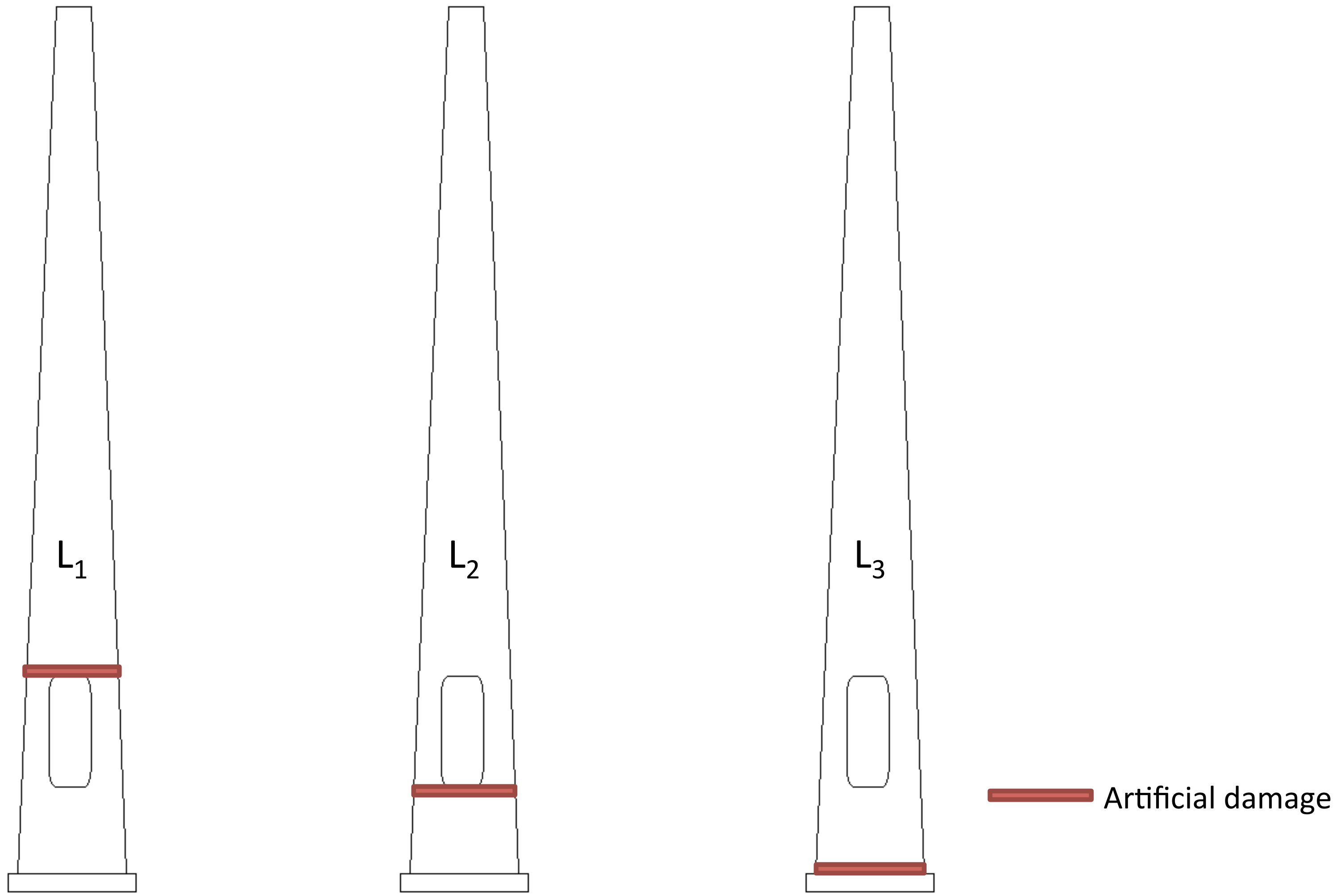
Most common damage locations:

Description	Finite Life Constant, $A \times 10^8$ (ksi^3 (MPa^3))	Threshold, $(\Delta F)_{TH}$ (ksi (MPa))	Potential Crack Location	Illustrative Example
SECTION 3 — HOLES AND CUTOUTS				
3.1 Net section of un-reinforced holes and cutouts.	250.0 (85200)	24.0 (165)	In tube wall at edge of unreinforced handhole.	
4.6 Full penetration groove-welded tube-to-transverse plate connections welded from both sides with back-gouging (without backing ring).	$K_F \leq 1.6$: 11.0 (3750) $1.6 < K_F \leq 2.3$: 3.9 (1330)	$K_I \leq 3.2$: 10.0 (69) $3.2 < K_I \leq 5.1$: 7.0 (48) $5.1 < K_I \leq 7.2$: 4.5 (31)	In tube wall at groove-weld toe.	

(Source: NCHRP Report, Cost-Effective Connection Details for Highway Sign, Luminaire, and Traffic Signal Structures)

Damage Simulations

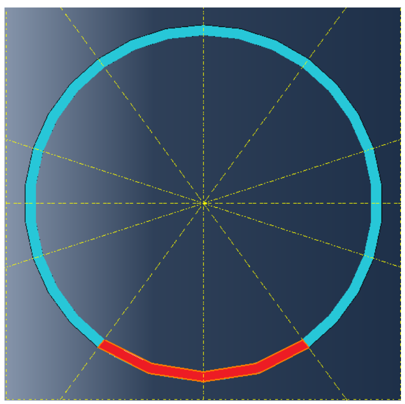
1. Location (L_j):
   Artificial damages have three damage location:L_1, L_2 and L_3.



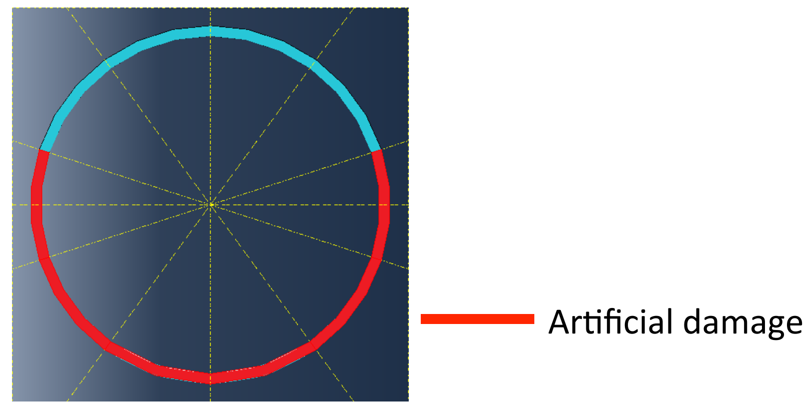
Damage Simulations

2. Damage sizes (ΔA):

Artificial damages have five different sizes, including: ΔA∈[0.2A, 0.4A, 0.6A, 0.8A, 1.0A] , where A is the total cross-sectional area.



0.2A – 20% Cross-sectional area is damaged (at location L3)



0.6A -- 60% Cross-sectional area is damaged (at location L3)

Damage Simulations

3. Damage level (ΔE):

Damages are simulated by reducing Young's Modulus in damaged regions. There are five levels: $\Delta E \epsilon [0.1, 0.3, 0.5, 0.7, 0.9]*E$, where E is the Young's modulus of materials.

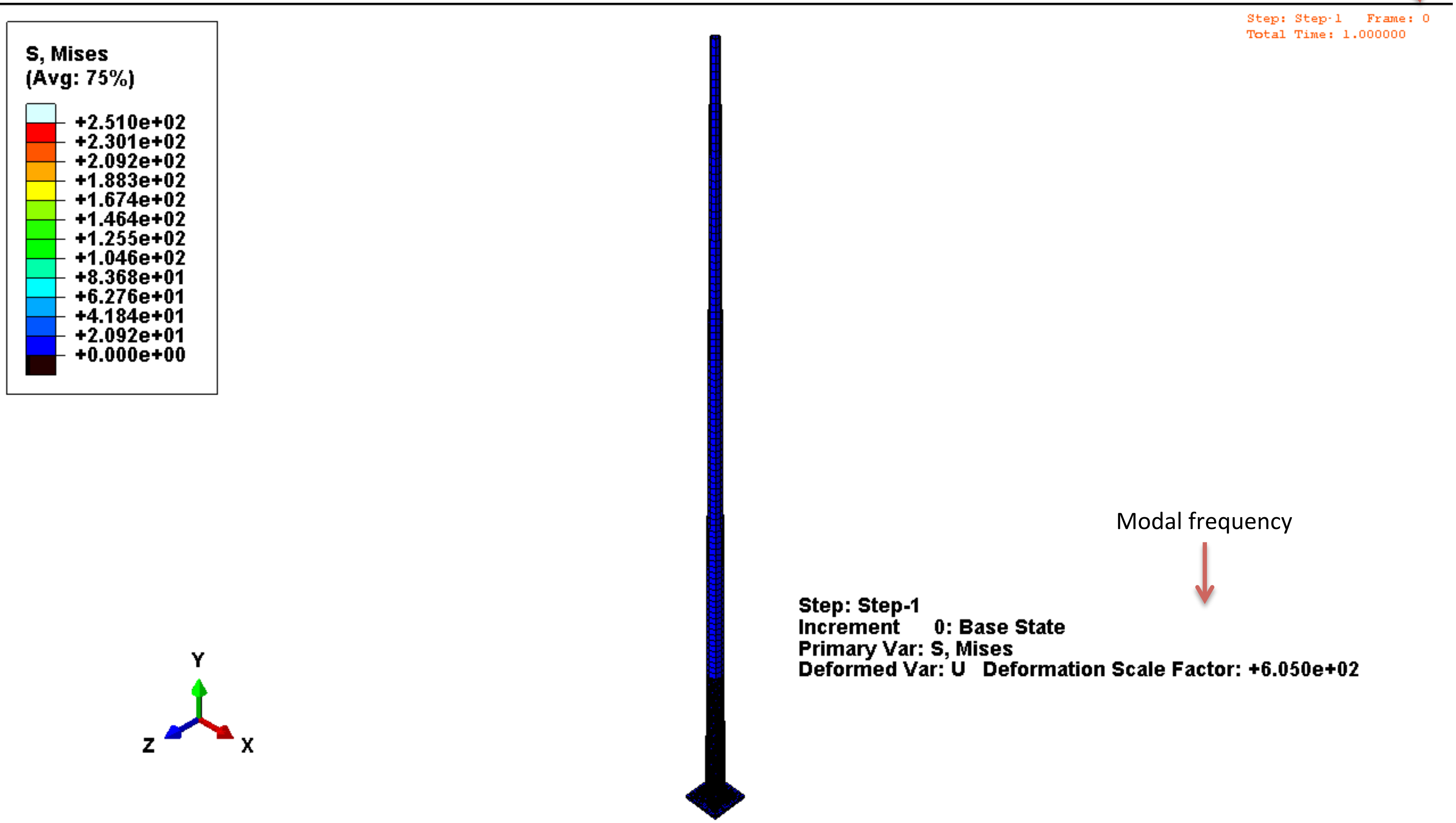
Group A														
ΔE=50% of Youngs modulus														
ΔA=20%			ΔA=40%			ΔA=60%			ΔA=80%			ΔA=100%		
Scenario A-1			Scenario A-2			Scenario A-3			Scenario A-4			Scenario A-5		
L_1	L_2	L_3	L_1	L_2	L_3	L_1	L_2	L_3	L_1	L_2	L_3	L_1	L_2	L_3

Group B														
Δ A=100% of total area														
ΔE=90%			ΔE=70%			ΔE=50%			ΔE=30%			ΔE=10%		
Scenario B-1			Scenario B-2			Scenario B-3			Scenario B-4			Scenario B-5		
L_1	L_2	L_3	L_1	L_2	L_3	L_1	L_2	L_3	L_1	L_2	L_3	L_1	L_2	L_3

Obtain first ten modal frequencies and mode shapes from different damaged models (listed above) and the intact model.

Damage Simulations

Mode number



Roadmap

Intact model

Modal parameters

First 10 modes modal frequencies/ mode shapes

Damaged models

Modal parameters

First 10 modes modal frequencies/ mode shapes

Find differences between intact and damaged models

Study the differences

Determine the relationships between artificial damages and modal frequencies/ mode shapes

Using the relationships to develop a damage detection methodology

Results and Discussion

Definition:

When an intact light pole is known, modal frequency difference can be computed by the following equation:

$$\Delta f_i^j = \frac{(f_i^j|_{intact} - f_i^j|_{damaged})}{f_i^j|_{intact}} * 100\%$$

where Δf_i^j is the model frequency difference of a damaged pole in i^{th} mode with a damage locating at L_j, $f_i^j|_{intact}$ is modal frequency of the intact model, and $f_i^j|_{damaged}$ is the modal frequency of a damaged model.

Results and Discussion

Definition:

Sensitive modes:

Out of the first ten modes, the modes whose modal frequency differences exceed a defined threshold value t_s.

Threshold value t_s : 1.25 times the average modal frequency differences of the first ten modes.

$$t_s = 1.25 \sum_{i=1}^{10} f_{ij} / 10$$

Results and Discussion

Definition:

Insensitive modes:

Out of first ten modes, the modes whose modal frequency differences are lower than a defined threshold value t_i.

Threshold value t_i : 0.25 times the average modal frequency differences of the first ten modes.

$$t_i = 0.25 \sum_{i=1}^{10} f_{ij} / 10$$

Results and Discussion

Definition:

Curvature of mode shapes can be computed by Central Difference equation:

$$\phi''(x)_n = \frac{\phi(x)_{n+1} - 2\phi(x)_n + \phi(x)_{n-1}}{d^2}$$

where $\phi(x)$ is the displacement of mode shape at node n, d is the distance between two nodes, and $\phi''(x)$ is the curvature of mode shape at node n.

Changes in curvature of mode shapes ($\Delta r_{\phi''}$) can be computed by the following equation:

$$\Delta r_{\phi_n''} = \frac{\phi_n''|_{damaged}}{\phi_n''|_{intact}}$$

Roadmap

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First 10 modes modal frequencies/ mode shapes

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Modal parameters

First 10 modes modal frequencies/ mode shapes

Find differences between intact an damaged models

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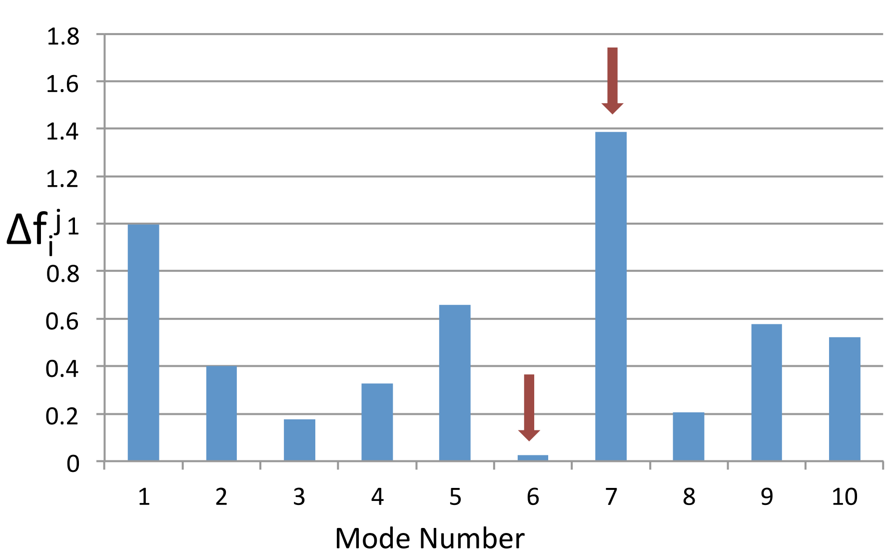
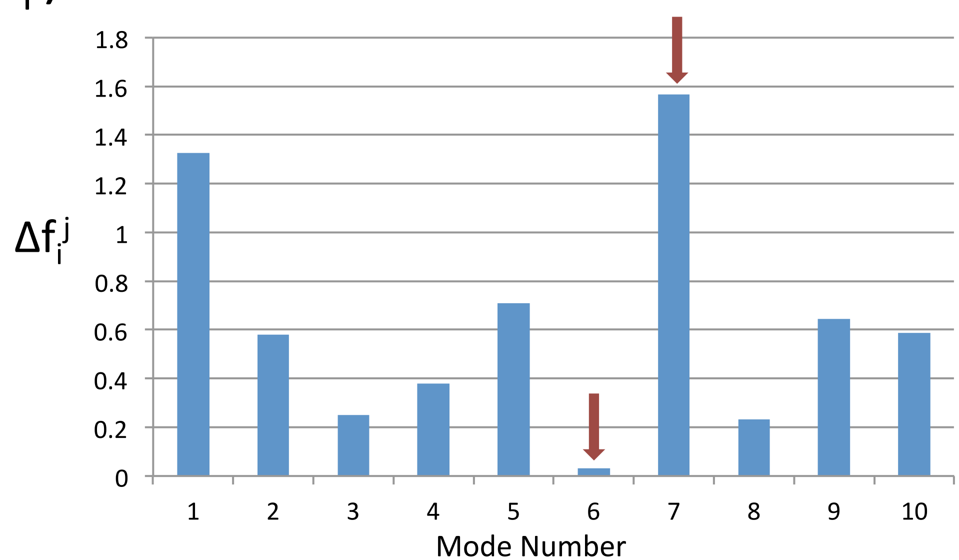
Summary of FE Results

Three patterns were found from FE results on modal frequencies and mode shapes.

1. In different damage scenarios with same damage location, some modes always have highest/lowest value in modal frequency differences (Δf_i^j).



Damage location: L1
Damage size: 40% A
Damage level: 50% E



Damage location: L1
Damage size: 100% A
Damage level: 50% E

Summary of FE Results

Sensitive/ insensitive modes for each damage location:

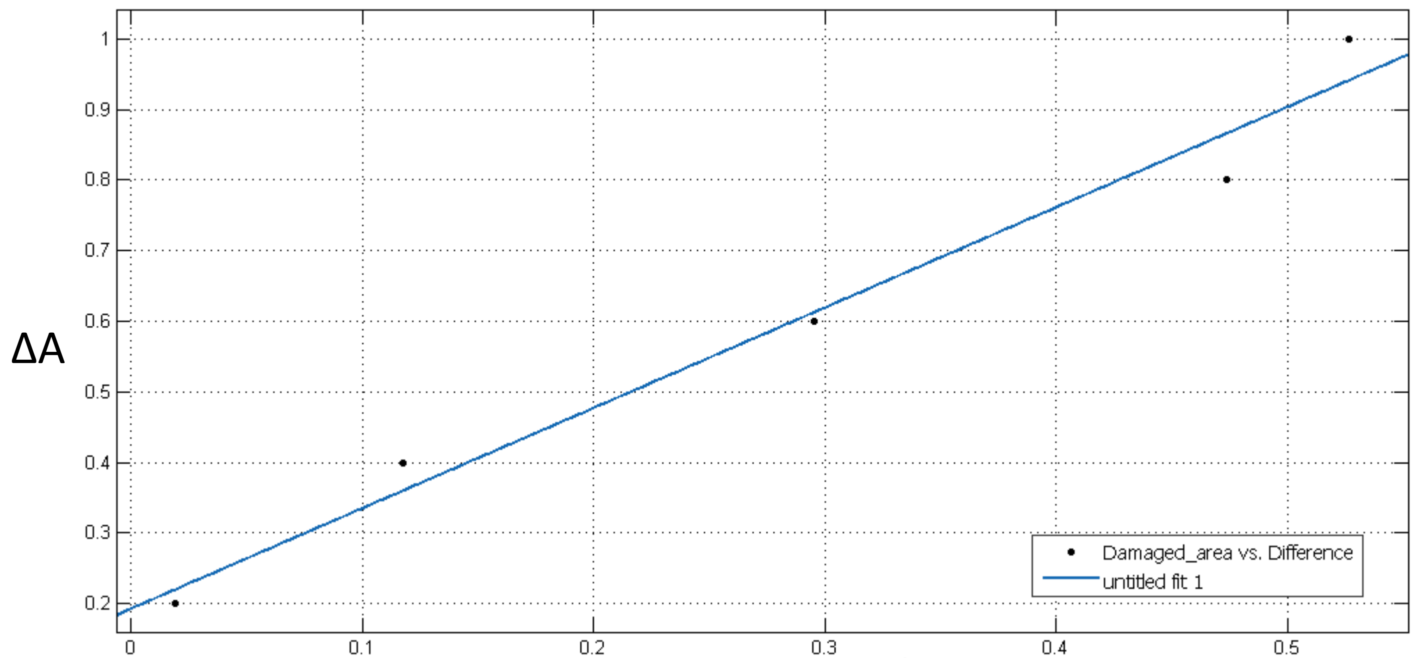
Table of sensitive/insensitive modes

Location	Sensitive modes	Insensitive modes
L_1	1, 7	6
L_2	1, 7	8, 10
L_3	9 or 10	7

→ **The combination of sensitive modes and insensitive modes is unique for each damage location.**

Summary of FE Results

2-1. Linear relationships were developed between damage size and modal frequency difference.



Modal frequency difference (Δf_2^1)

Quantification of Damages

Quantification of damage size α:

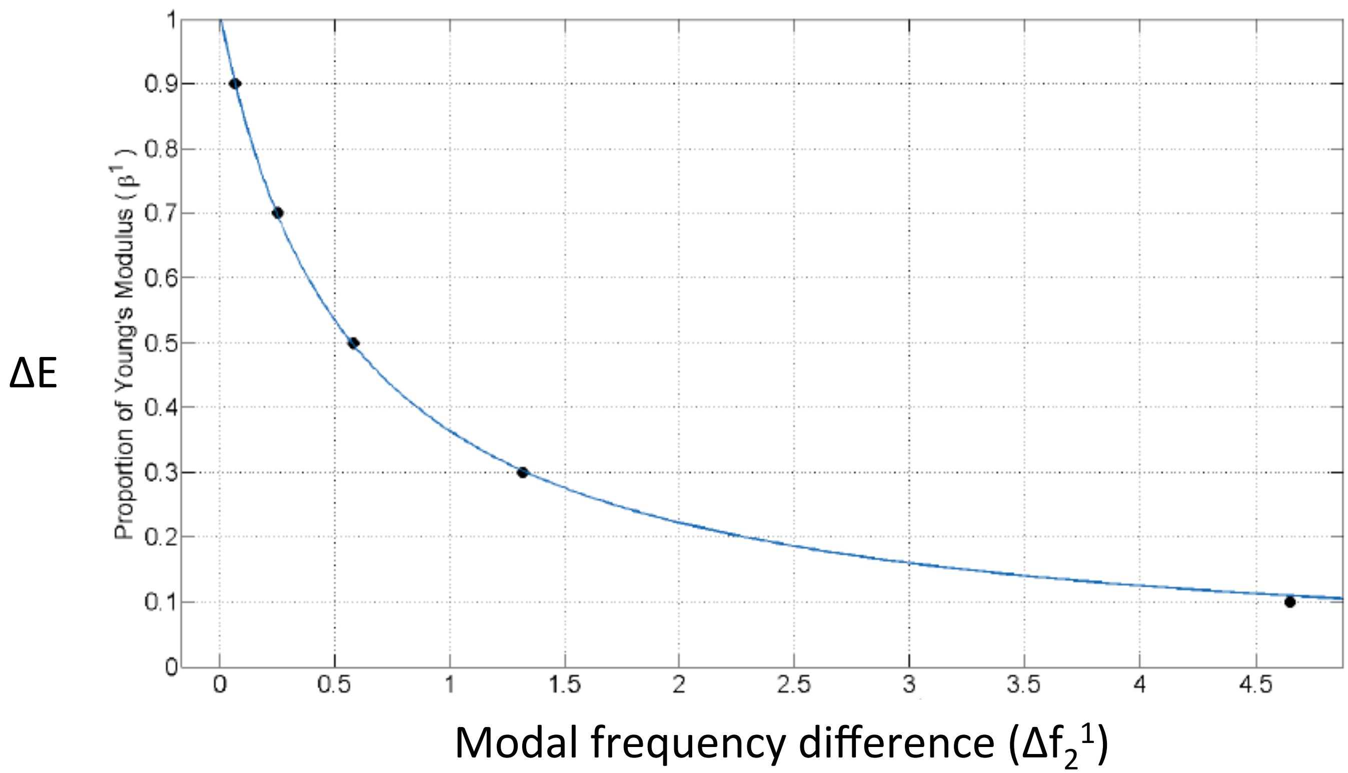
Linear relationships can be described by the following equation:

Damage size: $\alpha^j = a\Delta f_i^j + b$

Location(j)	Best-fit mode(i)	a	b	R^2
1	10	0.0255	0.4614	0.9841
2	6	0.0526	0.1665	0.9966
3	4	0.6858	-0.1251	0.9750

Quantification of Damages

2-2. Nonlinear relationships were developed between damage level (reduction in Young's modulus) and modal frequency difference.



Quantification of Damages

Quantification of damage level β:

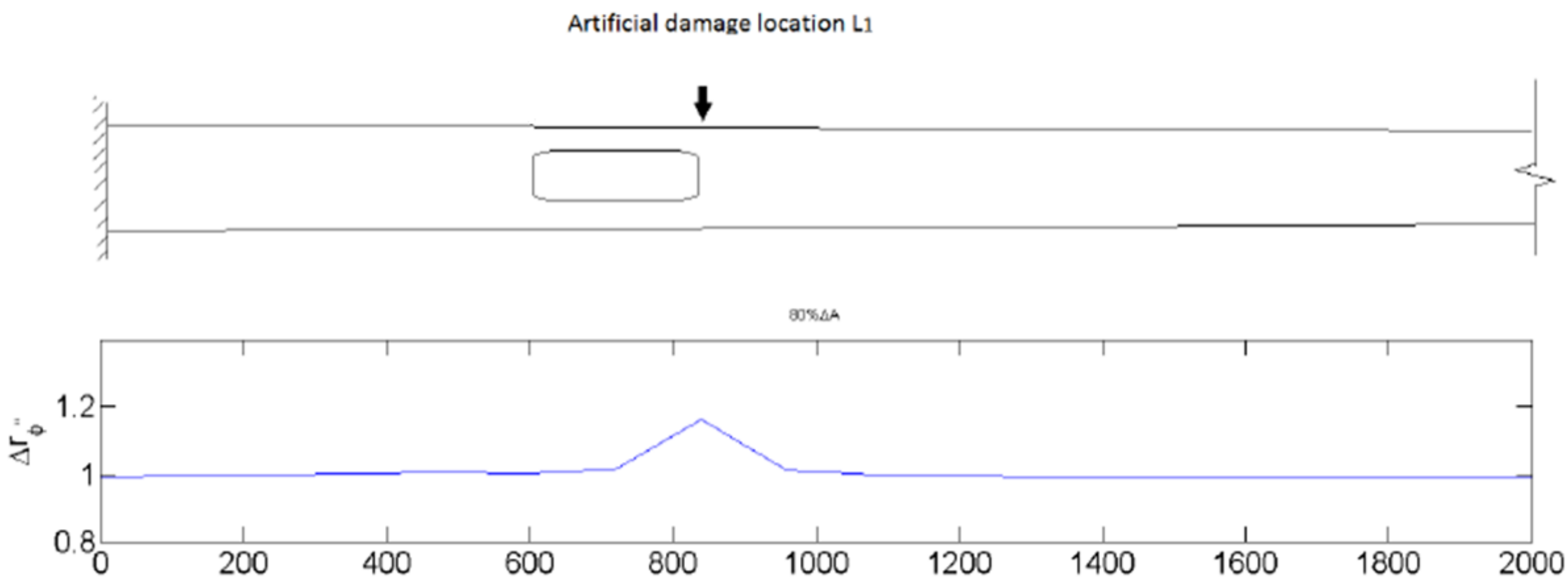
Relationship between damage level and modal frequency differences can be described by the following equation:

Damage level: $$\beta^j = c \ln(\Delta f_i^j) + d$$

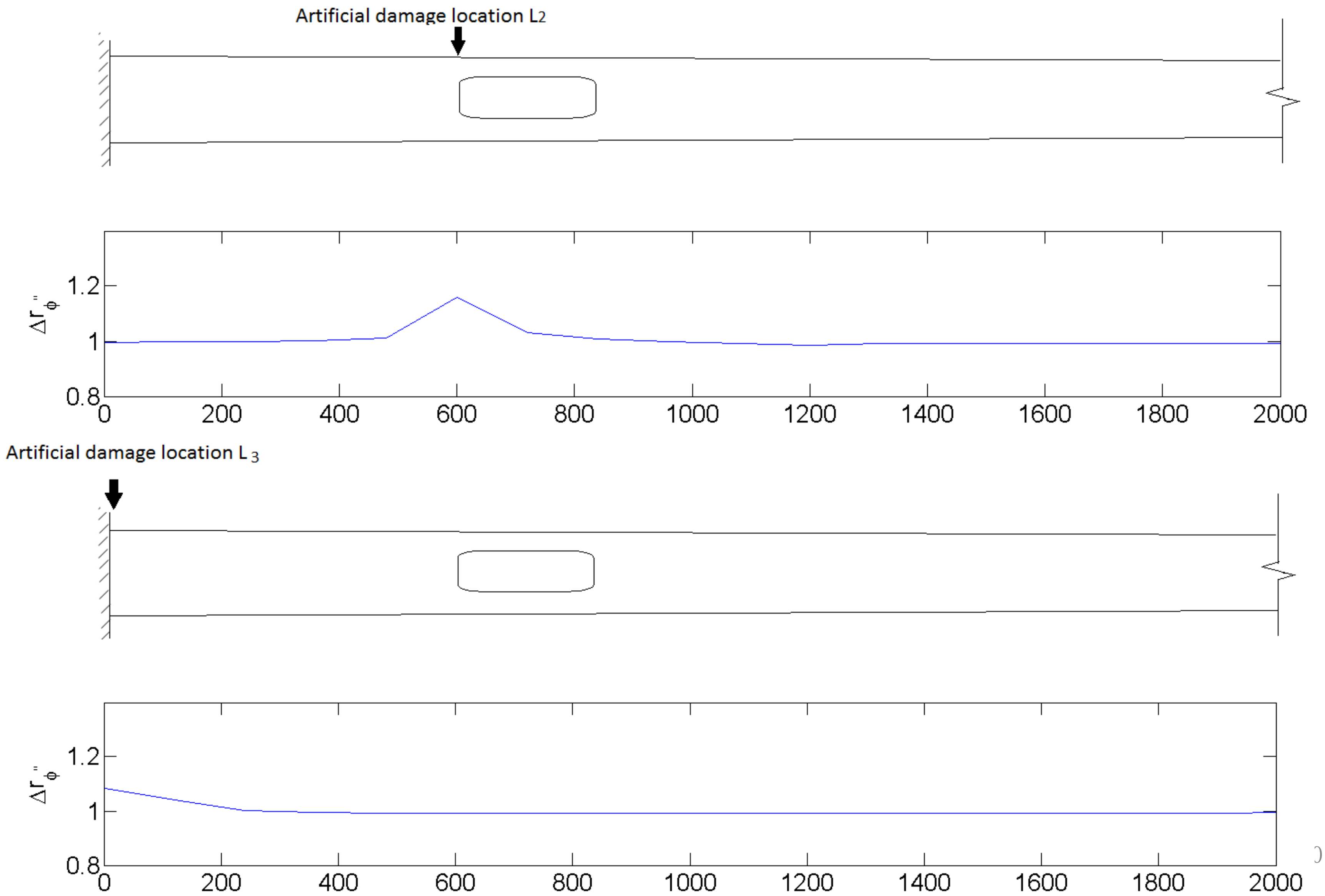
Location(j)	Best-fit mode(i)	c	d	R^2
1	2	-0.195	0.3900	0.9911
2	2	-0.194	0.3879	0.9914
3	8	-0.199	0.3628	0.9914

Summary of FE results

3. Curvatures of the second mode shape changes the most ($\Delta r_{\phi'',max}$) at damage location.



Summary of FE results



Special Case: Blind-test

- The intact light pole is unavailable.
- Modal frequencies of multiple light poles can always be obtained.

1) Pick an arbitrary light pole as a baseline instead of the intact light pole.
2) Use adjusted equation to compute modal frequency differences.

$$\Delta f_i^j = \left| \frac{(f_i^j|_{baseline} - f_i^j|_{damaged})}{f_i^j|_{baseline}} \right| * 100\%$$

3) Determine the sensitive/insensitive modes using moving thresholds t_s and t_i.
4) Check the following table and determine the damage location.

Location	Sensitive modes	Insensitve modes
L1	1,7	6
L2	1,7	8
L3	10	7

Special Case: Blind-test

Constraints:

- Damages can only occur at L_1, L_2 or L_3.
- First ten modal frequencies of light pole are required.
- Damages can not be quantified.

Roadmap

Intact model

Modal parameters

First 10 modes modal frequencies/ mode shapes

Damaged models

Modal parameters

First 10 modes modal frequencies/ mode shapes

Find differences between intact an damaged models

Study the differences

Determine the relationships among artificial damages and modal frequencies/ mode shapes

Using the relationships to develop a damage detection methodology

Proposed Damage Detection Methodology

1. Extract first 10 modal frequencies/ mode shapes from an intact model & unknown models;
2. Compute the modal frequency differences and changes in mode shapes of the unknown light poles;
3. Compute thresholds t_s and t_i, and use them to identify sensitive/insensitive modes;
4. Locate the damage by checking the combination of sensitive and insensitive modes of unknown light poles in *Table of sensitive/insensitive modes*; or locate the damage by finding $\Delta r_{\phi'',max;}$
5. Use obtained empirical equations to quantify the damage.

Conclusions

1. Locate damage using modal frequency -- Since the combination of sensitive modes and insensitive modes is unique for each damage location, one can locate the damage of light pole by checking the following table:

Table of sensitive/insensitive modes

Location	Sensitive modes	Insensitive modes
L_1	1, 7	6
L_2	1, 7	8, 10
L_3	9 or 10	7

Conclusions

2. Quantify damage -- Substitute modal frequency difference into following equations:

Damage size: $\alpha^j = a\Delta f_i^j + b$

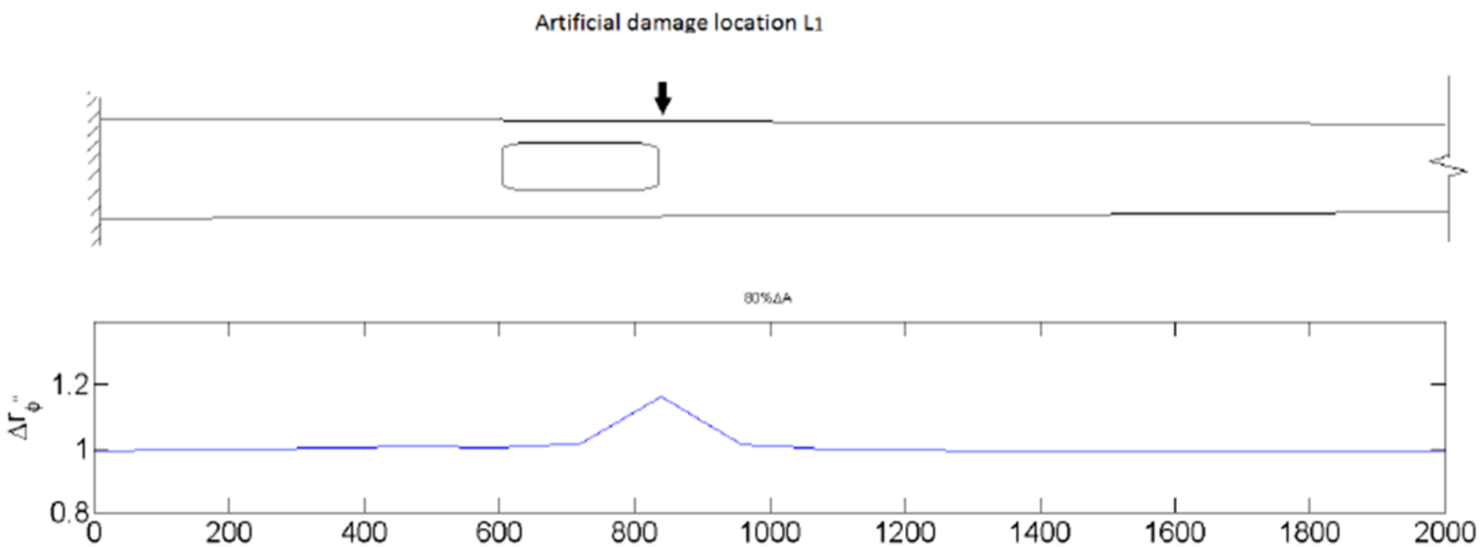
Damage level: $\beta^j = c\ln(\Delta f_i^j) + d$

Location(j)	Best-fit mode(i)	a	b	R^2
1	10	0.0255	0.4614	0.9841
2	6	0.0526	0.1665	0.9966
3	4	0.6858	-0.1251	0.9750

Location(j)	Best-fit mode(i)	c	d	R^2
1	2	-0.195	0.3900	0.9911
2	2	-0.194	0.3879	0.9914
3	8	-0.199	0.3628	0.9914

Conclusions

3. Locate damage using mode shape curvature -- In the second mode, maximum curvature change ($\Delta r_{\phi'',max}$) indicates damage location. Therefore, one can use changes in curvature of the second mode shape to locate damages. However, this method is **limited**.
   - When damage size is greater than 80% of cross-sectional area, the maximum curvature changes accurately indicate damage locations.

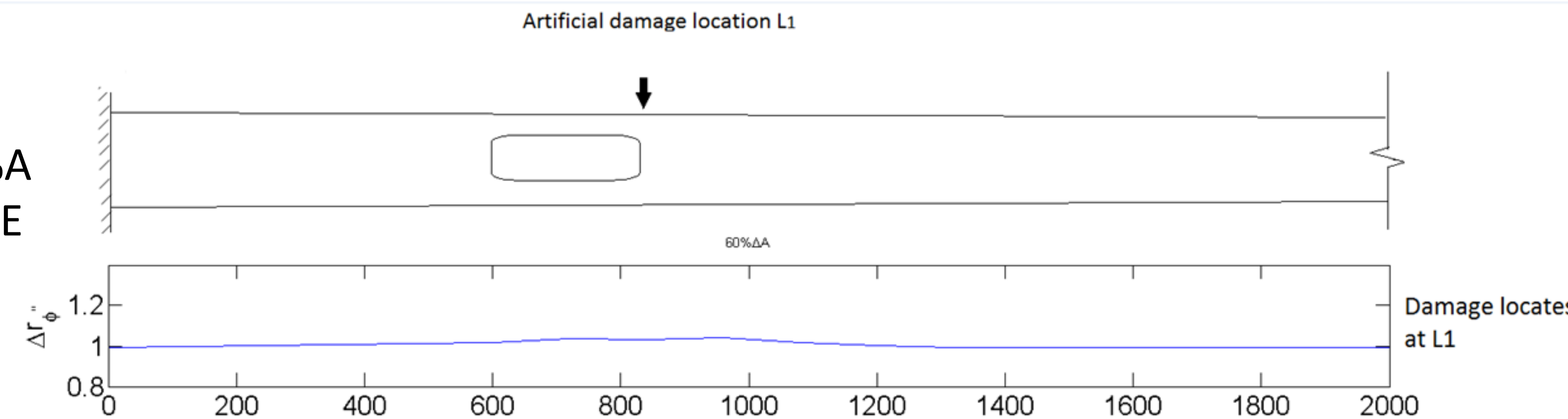


ΔA=80%A
ΔE=50%E

Conclusions

- When damage size is between 40% to 60% of cross-sectional area, there will be shifts between the maximum curvature change location and damage location.

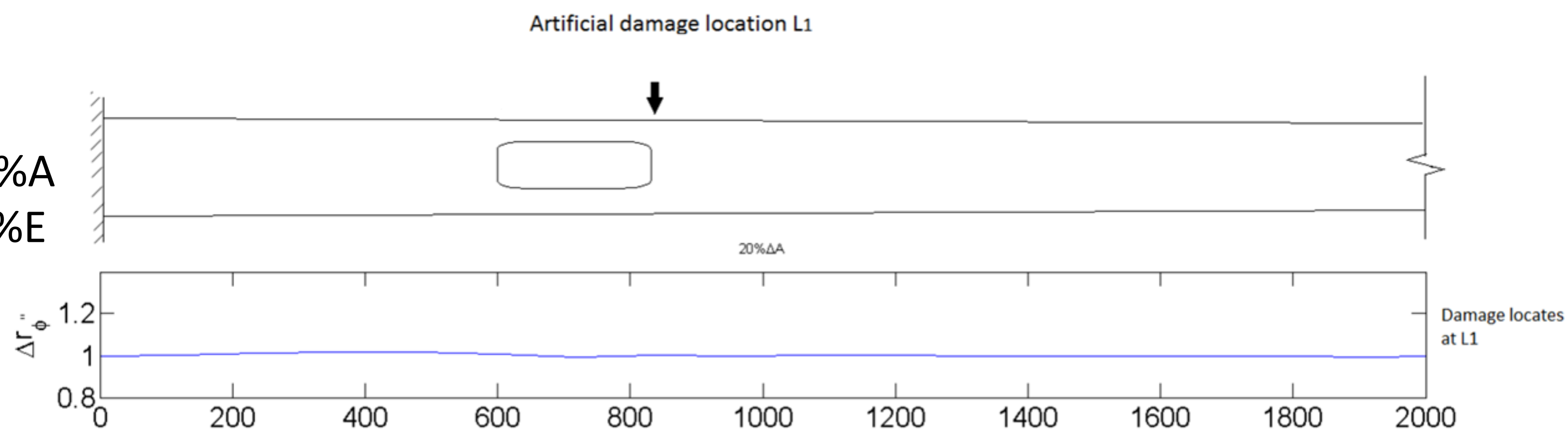
ΔA=60%A
ΔE=50%E



Conclusions

- When damage size is smaller than 20% of cross-sectional area, the curvature change is not sensitive enough to locate the damage.

ΔA=20%A
ΔE=50%E



When ΔA is smaller than 80%A, maximum curvature change ($\Delta r_{\phi'',max}$) of the second mode is not sensitive enough to locate damage.

Contributions

- Sensitive modes and insensitive modes of light poles are defined, and their combinations are found to be unique for each damage location.
- Two empirical equations were proposed for damage quantification.
- A damage detection methodology is proposed to identify the damages in a light pole structure using its dynamic responses (modal frequencies and mode shapes) in free vibration.

Future Work

- Conduct experiments to confirm the FE simulation results.
- Develop a method to quantify the damages (specifically, damage's size and level) using changes in mode shape curvature.
- Develop a damage detection methodology using fewer (e.g., 4) modal frequencies.
- Explore more damage locations (e.g., the conjunctive weld between pole and base plate).

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Appendix

Validation of sensitive modes:

Gudmunson [15] proposed the following equation which relates fractional changes in modal strain energy and modal frequency:

$$\frac{\delta W_i}{W_i} = \frac{\delta \omega_i^2}{\omega^2}$$

where W_i is the *i*th modal strain energy of the intact structure, δW_i is the loss in the *i*th modal strain energy after damage, and $\delta \omega^2 / \omega^2$ is the fractional change in the *i*th eigenvalue (modal frequency difference) due to the damage.

$$\delta W_i \uparrow \;\Longrightarrow\; \delta \omega_i^2 \uparrow$$

Appendix

Kim *et. al.*[20] proposed following equation to compute δW_i of a simple supported beam structure:

$$\delta W_i = \left(\frac{\pi t(1-\nu^2)}{2E} F^2 \sigma_k^2 a_k^2 \right)_i$$

in which, for the *i*th mode, a_k represents the damage size (depth) at location *k* and σ_k represents the maximum flexural stress at location *k* along the beam's longitudinal axis, *t* is the beam thickness, *E* is Young's modulus, ν is Poisson's ratio and *F* is a geometrical factor depending on the dimensionless crack-length/beam-depth ratio a/H.

π, t, ν, E, F, a_k are constant.

$$\sigma_k \uparrow \Rightarrow \delta W_i \uparrow \Rightarrow \delta\omega_i^2 \uparrow$$

Appendix

Therefore, the mode which have largest modal frequency difference $\delta\omega_i$ has the maximum value of $\Delta\sigma_k^2$ (difference between intact and damaged structures).

$$\delta\omega_{i\;,max}^{2} \Longrightarrow \Delta\sigma_{k,\,max}$$

Appendix

The longitudinal stress of an arbitrary point *m* in this cross-section is:

$$\sigma_m = \frac{M(x)c_m}{I}$$

For an Euler-Bernoulli beam, its bending moment at location x is:

$$M(x) = -EI\frac{d^2\phi(x)}{dx^2} = -EI\phi''(x)$$

where *E* is Young's modulus, *I* is moment of inertia of the beam cross-section at location x, ϕ(*x*) is the displacement of the beam and ϕ''(*x*) is the curvature of the mode shape.

$$\Longrightarrow \sigma_m = -c_m E\phi''(x)$$

Appendix

then,

$$\Delta\sigma_m = \frac{\sigma_m - \sigma_m^*}{\sigma_m} = \frac{-c_m E\phi''(x) - (-c_m E^*\phi''^*(x))}{-c_m E\phi''(x)} = 1 - j\frac{\phi''^*}{\phi''}$$

where *E*∗ is Young's modulus of damaged materials, and *j* is the ratio between *E* and *E**.

Also,

$$\phi''(x)_n = \frac{\phi(x)_{n+1} - 2\phi(x)_n + \phi(x)_{n-1}}{d^2}$$

$$\frac{\phi''^*(x)_n}{\phi''(x)_n} = \frac{\phi^*(x)_{n+1} - 2\phi^*(x)_n + \phi^*(x)_{n-1}}{\phi(x)_{n+1} - 2\phi(x)_n + \phi(x)_{n-1}}$$

Appendix

Let $\phi^{*}(x)_n = \phi(x)_n + \delta_n$, where δ_n is the differential displacement between $\phi^{*}(x)_n$ and $\phi(x)_n$,

$$\frac{\phi''^{*}(x)_n}{\phi''(x)_n} = \frac{(\phi(x)_{n+1} + \delta_{n+1}) - 2(\phi(x)_n + \delta_n) + (\phi(x)_{n-1} + \delta_{n-1})}{\phi(x)_{n+1} - 2\phi(x)_n + \phi(x)_{n-1}}$$

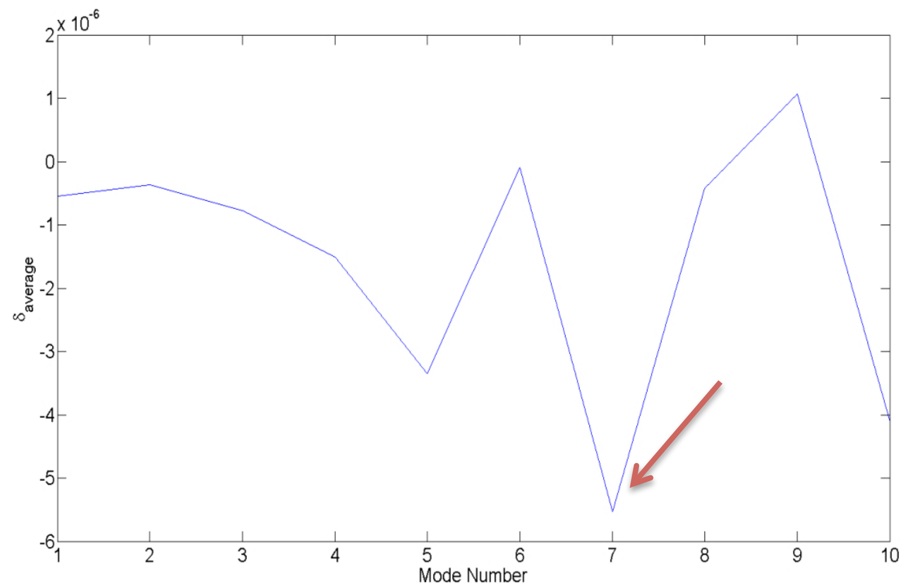
$$= 1 + \frac{\delta_{n+1} - 2\delta_n + \delta_{n-1}}{\phi(x)_{n+1} - 2\phi(x)_n + \phi(x)_{n-1}}$$

$$\delta_{n+1} - 2\delta_n + \delta_{n-1} \,|_{\min} \Longrightarrow \frac{\phi''^{*}(x)_n}{\phi''(x)_n}\Big|_{\min} \Longrightarrow \Delta\sigma_{k,\,max} \Longrightarrow \delta\omega_{i\ max}^{2}$$

Appendix

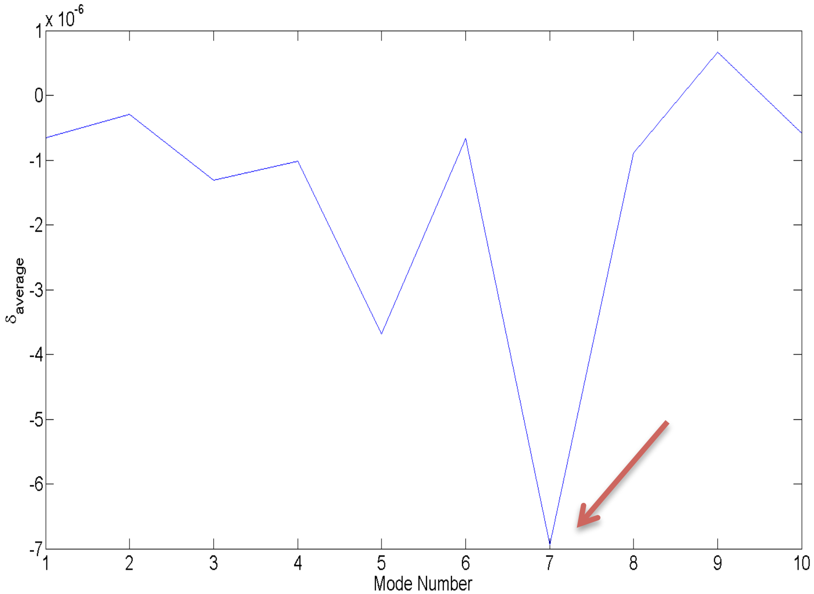
Example: Damage scenario A-5 (ΔA=100%, ΔE=50%).

The modes with the minimum value of $\delta_{n+1} - 2\delta_n + \delta_{n-1}$ for each damage location are: L_1–7th Mode; L_2–7th Mode; and L_3–10th mode.

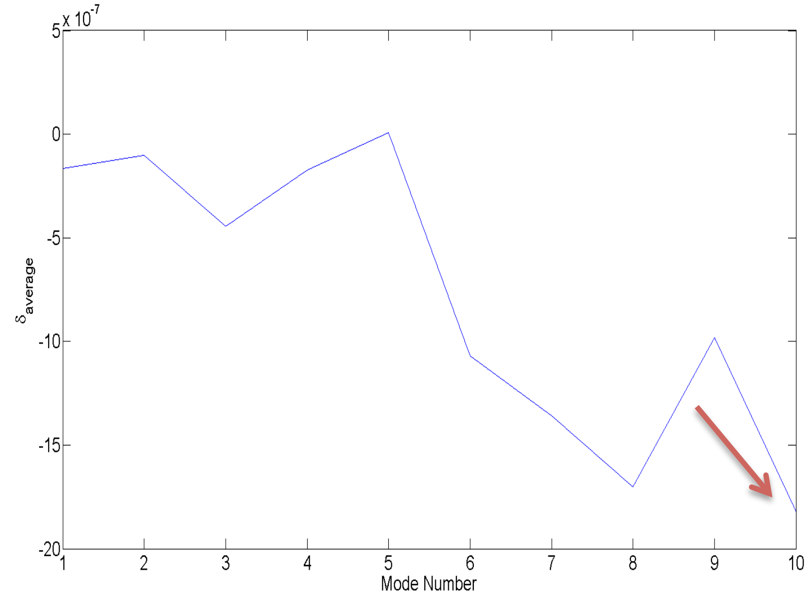


L_1–7th Mode

Appendix



L_2–7th Mode



L_3–10th mode

Appendix

Compare with the most sensitive modes identified from FE models, the theoretical derivation results show a good agreement with FE results.

	Most sensitive mode	Minimum $\delta_{average}$
L_1	7th mode	7th mode
L_2	7th mode	7th mode
L_3	10th mode	10th mode